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**Final report for**

# A TWO-DIMENSIONAL LASER INTERFEROMETER SYSTEM FOR DYNAMIC RESPONSE CHARACTERIZATION

A DURIP Project Sponsored by the
Air Force Office of Scientific Research

**by**


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AFOSR Program Manager:
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The objective of this AFOSR DURIP (Defense University Research Instrumentation Program) grant was to establish experimental capabilities for quantifying material responses under highly dynamic conditions. The parent grant with which this grant is associated is entitled **"Time-Resolved Analysis of the Dynamic Behavior of Granular Materials"**. The capabilities have been established and have been used in the research. A state-of-the-art laser interferometer system has been acquired to allow simultaneous measurement of surface velocities at four independent points. This aspect exceeded the original goal of two independent measurements. This multi-channel VISAR system provides two-dimensional time-resolved motion measurement capability necessary for the full characterization of deformation states in pressure-shear impact experiments. This novel capability is the first of its kind in a university in the United States. Along with Georgia Tech's internal stress (PVDF gauge) diagnostics for plate impact experiments acquired separately under an Army Research Office (ARO) grant, this VISAR system has allowed the constitutive and failure behaviors of concrete and mortar to be characterized in the parent grant. The capabilities established are novel in nature and will allow the constitutive, failure, post-failure, and interfacial behavior of materials at very high strain rates to be investigated in current as well as future AFOSR and DoD research.

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## Executive Summary

The objective of this AFOSR DURIP (Defense University Research Instrumentation Program) grant was to establish experimental capabilities for quantifying material responses under highly dynamic conditions. The parent grant with which this grant is associated is entitled **"Time-Resolved Analysis of the Dynamic Behavior of Granular Materials".** The capabilities have been established and have been used in the research. A state-of-the-art laser interferometer system has been acquired to allow simultaneous measurement of surface velocities at four independent points. This aspect exceeded the original goal of two independent measurements. This multi-channel VISAR system provides two-dimensional time-resolved motion measurement capability necessary for the full characterization of deformation states in pressure-shear impact experiments. This novel capability is the first of its kind in a university in the United States. Along with Georgia Tech's internal stress (PVDF gauge) diagnostics for plate impact experiments acquired separately under an Army Research Office (ARO) grant, this VISAR system has allowed the constitutive and failure behaviors of concrete and mortar to be characterized in the parent grant. The capabilities established are novel in nature and will allow the constitutive, failure, post-failure, and interfacial behavior of materials at very high strain rates to be investigated in current as well as future AFOSR and DoD research.

## 1. Abstract of Parent Research Project:

The parent project was initiated in January 1997. The objectives of this research was to (1) obtain material response data and constitutive characterization for concrete and mortar at strain rates of up to $10^5$ $s^{-1}$, (2) analyze the evolution of load-carrying and energy absorption capacities, and (3) understand deformation and failure mechanisms under high pressures and high strain rates, such as fragmentation, comminution and shear flow localization. The motivations for this proposal are (1) the need of the U.S. Air Force to characterize the response of granular materials such as concrete and sand under dynamic loading from blast or penetration, as demonstrated by a recent bomb explosion in Saudi Arabia; (2) the need to predict possible improvement in structures involving such materials, as demonstrated in combat during the gulf war; and (3) the current lack of data and characterization for the material behavior at the high-pressure (up to 6 GPa) and high-strain-rate (up to $10^5$ $s^{-1}$) conditions. This effort has advanced the current understanding of the dynamic constitutive response, failure mechanisms and damage mitigating capability of granular and particulate materials.

## 2. Descriptions of Experiments Capabilities

Two types of impact experiments are used to achieve loading at high strain rates *over a range of multiaxial states of stress*. The first type is normal impact (see Fig.1) and the second type is pressure-shear impact (see Fig. 2). The normal impact configuration allows the strength and stress-carrying capacity of materials to be evaluated at strain rates above 10 $s^{-1}$. The pressure-shear impact configuration allows both a pressure and a shear stress component to be applied to the specimen. By varying the impact angle $\theta$, a range of pressure and shear stress ratios can be obtained. This configuration can also be used to analyze the interfacial interactions between concrete and metals, as shown in Fig. 3. Specifically, when the impact angle $\theta$ is sufficiently large, sliding will occur. The particular arrangement in Fig. 3 makes it possible to infer the interfacial normal stress $\sigma(t)$ and shear stress $\tau(t)$ from measured normal velocity u(t) and transverse velocity v(t) at the rear surface of the target (metal, simulating penetrator material), i.e.

$$\sigma(t) = \tfrac{1}{2}\rho c_1 u(t) \text{ and}$$
$$\tau(t) = \tfrac{1}{2}\rho c_2 v(t),$$

where $\rho c_1$ and $\rho c_2$ are the normal and shear wave impedances of the target (metal) material. These experiments simulate the conditions of impact and penetration.

The multibeam VISAR laser interferometer system acquired through this DURIP grant allows the measurements required in these experiments. In Fig. 1, four independent measurements are made to characterize the effect of material heterogeneity on dynamic response. In Figs. 2&3, both the in-plane and the out-of-plane components of the surface velocity are measured to fully characterize the deforamtion.

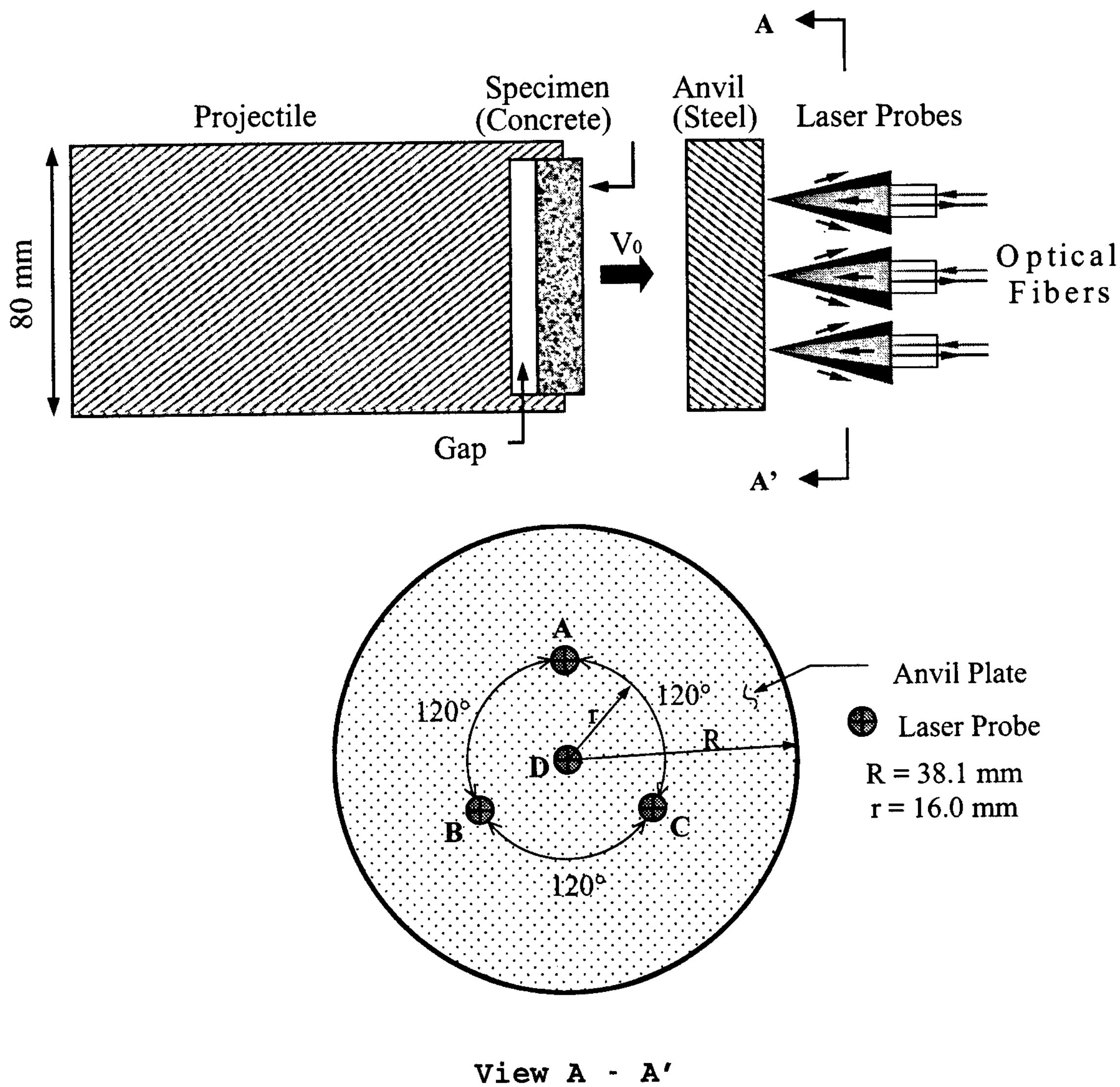


*Fig. 1 Normal Impact Experiment of Granular Materials*

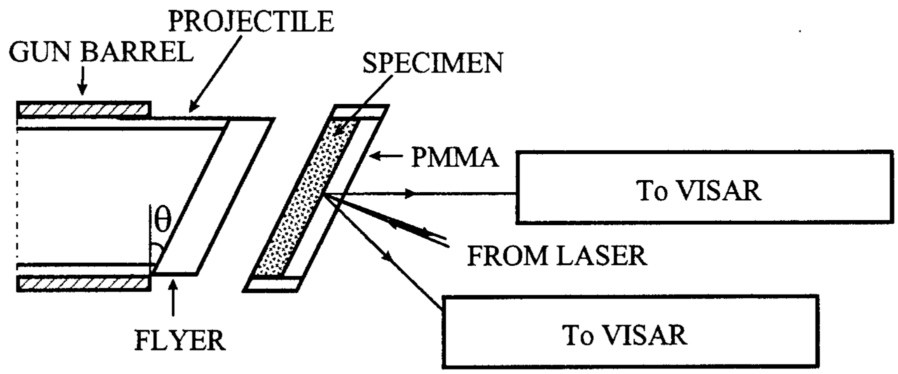


*Fig. 2 Pressure-shear Impact Experiment with Two independent VISAR measurements for Combined in-plane and out-of-plane Velocity Determination*

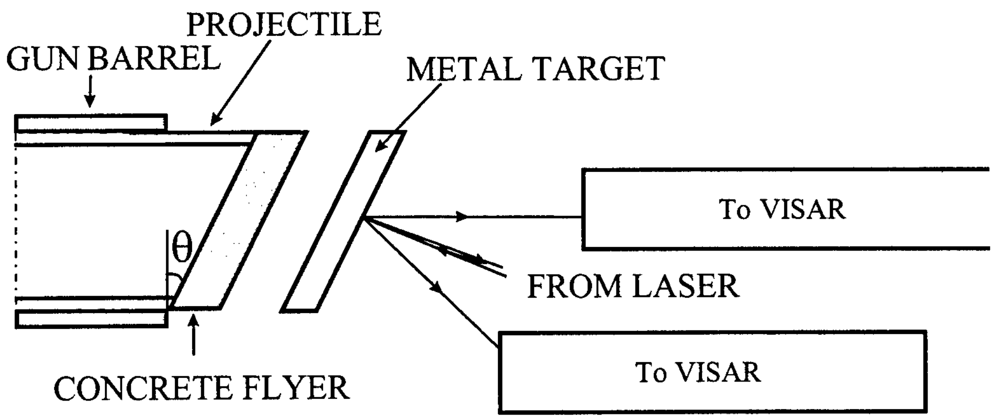


*Fig. 3 Pressure-shear Impact Experiment for the Analysis of Target/Penetrator Interfacial Interactions*

## 3. PHYSICAL SYSTEM:

The multi-beam VISAR system consists of a central unit, control modules, a lasers, and fiber probes. The components are shown in the following figures.

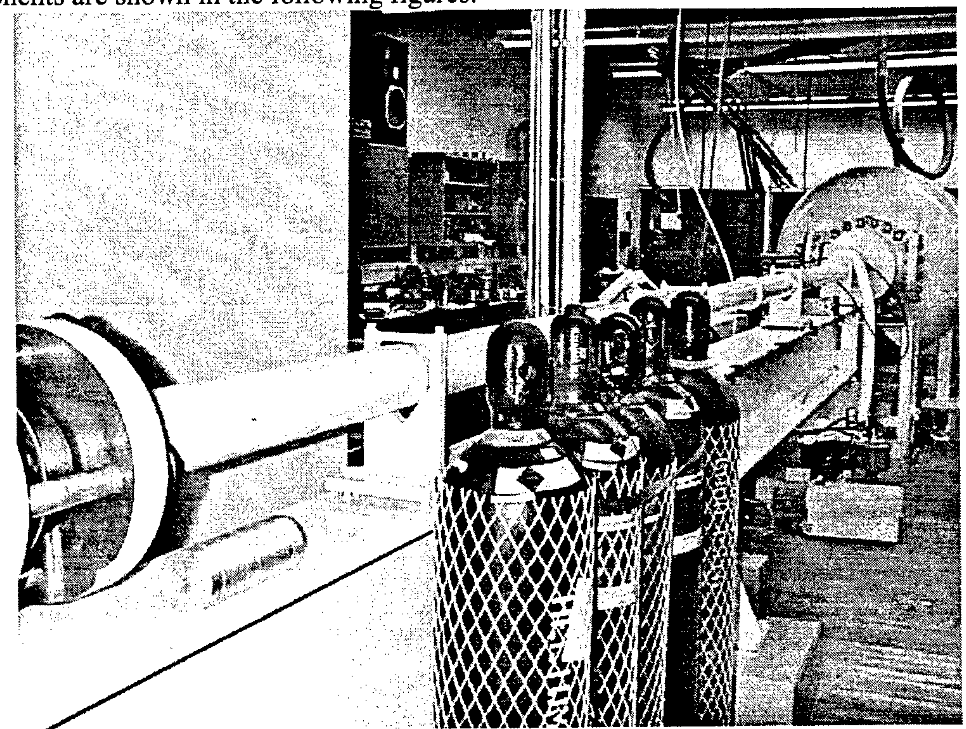

*Fig.4 Gas Gun facility at Georgia Tech*

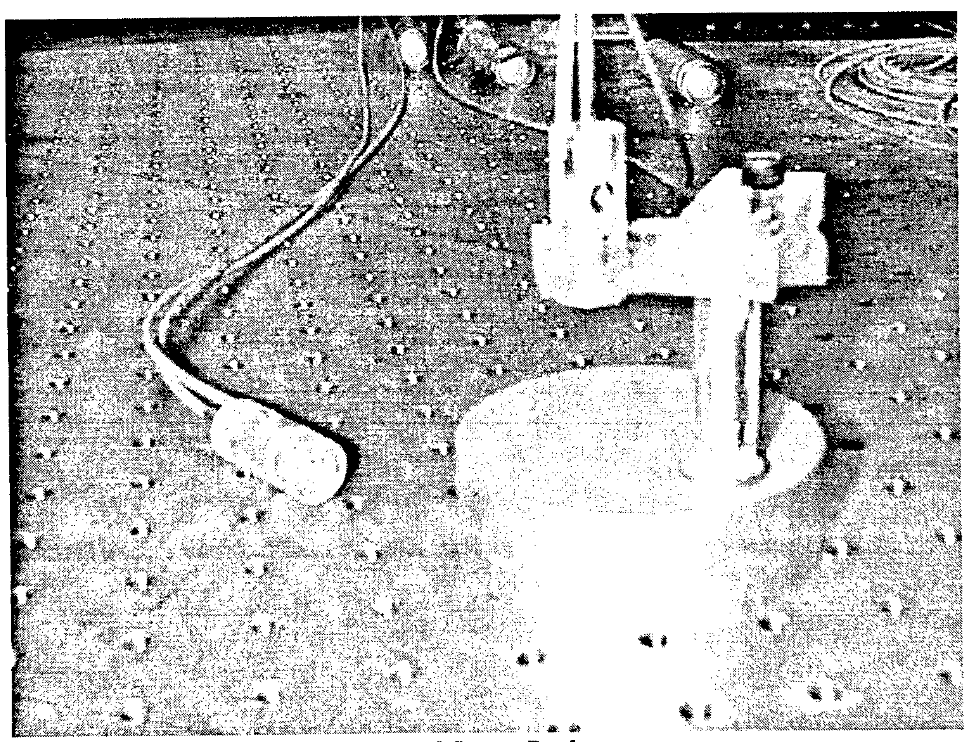

*Fig.5 Laser Probe*

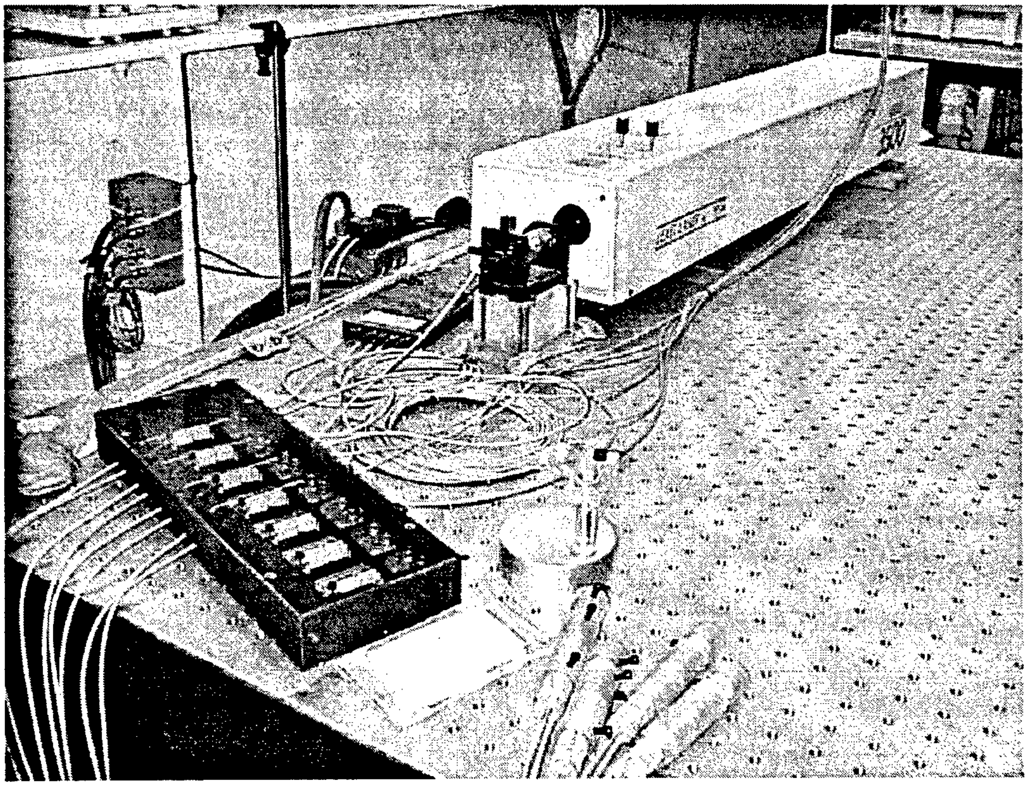

Fig. 6 *Laser and Multi-beam fiber splice board*

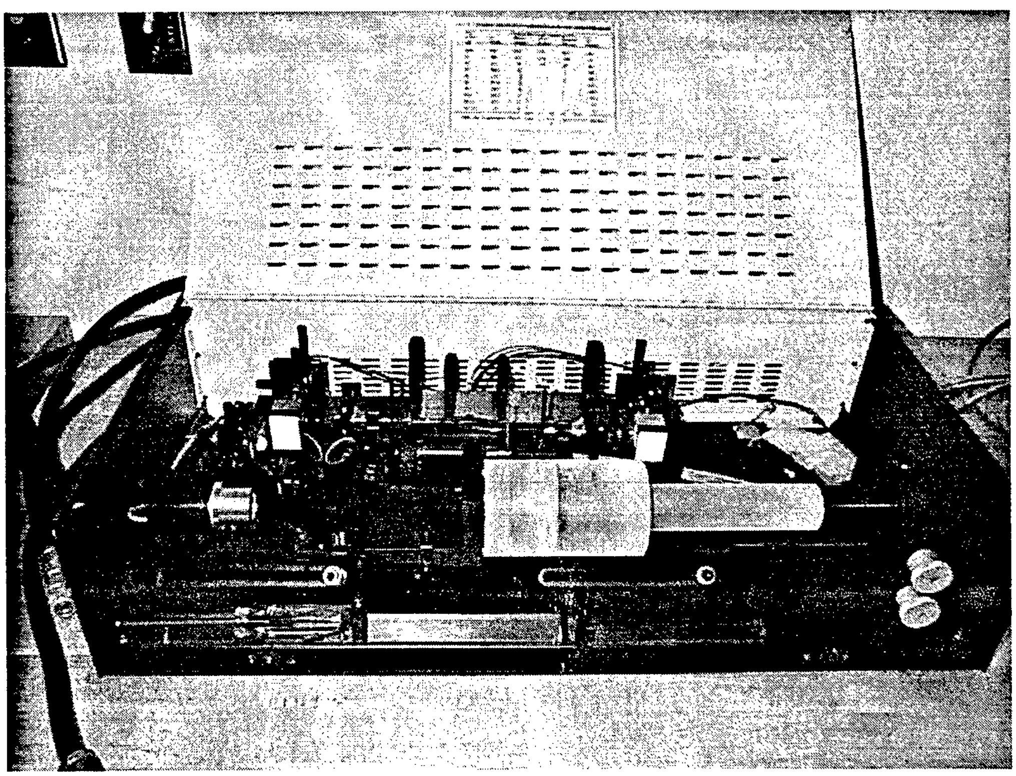

*Fig. 7 Multi-beam VISAR Control Unit*

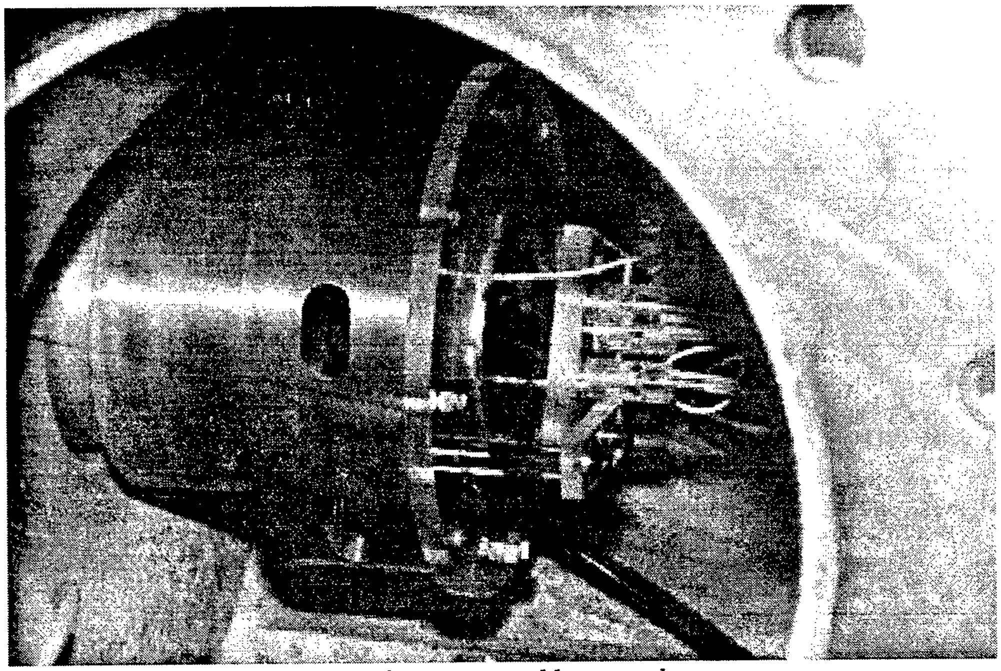

*Fig. 8 Target configuration and laser probes on a target*

## 4. BRIEF SUMMARY OF SOME RESULTS OBATINED WITH THIS SYSTEM:

Plate impact provides a unique means to generate extremely high strain rates and high pressures under well-controlled conditions. In this study, normal impact experiments are conducted on circular disks of concrete and mortar to characterize their dynamic stress-carrying capacities. Average strain rates achieved are on the order of $10^4$ $s^{-1}$. Since attention is focused on the time period before cylindrical unloading waves arrive at the center of the impacted specimen, the central region remains in a state of nominally uniaxial strain due to lateral inertial confinement. Confining pressures in the experiments conducted are on the order of 1 - 1.5 GPa.

A schematic illustration of the impact configuration is shown in Fig. 1. The specimens are 76.2 mm in diameter and 10 mm in thickness. The end surfaces are lapped flat and the actual thickness is within 0.0254 mm of 10 mm. The specimen is placed at the front of the projectile assembly. A gap between the disk specimen and the projectile tube is provided to allow a traction-free end condition for the back surface of the specimen during the impact process. The specimen impacts against an anvil plate made of hardened Hampden tool steel. The target steel is heat-treated to have a hardness of approximately 65 on the Rockwell C scale and has a thickness of 13.5 mm. The projectile is propelled by pressurized helium gas. The impact occurs in a vacuum chamber located at the muzzle end of a gas gun.

The velocity of the projectile $V_0$ is measured immediately prior to impact using wire pins.

Upon impact, compressive stress waves are generated in both the specimen and the anvil plate. These waves propagate from the impact face toward the rear surface of the specimen and the rear surface of the anvil plate. Upon arriving at the rear free surfaces, these compressive waves are reflected as tensile waves. The reflected tensile waves then interfere destructively with the on-going incident compressive waves, reducing the compressive stresses in the specimen. The normal particle velocities at four points on the rear surface of the anvil plate are measured using a VISAR (Velocity Interferometer System for Any Reflector) laser interferometer system with an accuracy of $\pm 2$ $ms^{-1}$. The four simultaneous measurements are made using four independent laser probes arranged as shown in Fig. 1. One probe (D) is focused at the center and the other three (A, B, and C) are focused on three points on a circle around the center. The latter probes are evenly spaced on the circle and have a distance of 16 mm to the specimen center. The simultaneous measurements of velocities at different locations provide an opportunity for analyzing the heterogeneous deformation in the specimen. The interference signals from the laser interferometers are detected by photodiodes and recorded on a Tektronix TDS 784A digital oscilloscope with sampling rates of up to 4 billion samples per second.

The time-distance diagram shown in Fig. 8 indicates schematically how the waves propagate in the concrete specimen and the steel anvil plate during the impact process. The diagram is based on the one-dimensional wave propagation theory and the lines represent the longitudinal wave fronts at given position and time. The construction of this diagram assumes that the materials involved are homogeneous and linearly elastic. This assumption does not consider the significant inelastic deformation and the material heterogeneity in the specimen. Therefore, this illustration should be viewed as an approximate representation for various wave fronts and guide for experiment design. This diagram is also useful for the analysis and interpretation of experimental results. In addition to the nominally planar wave fronts, a cylindrical release wave also develops in the specimen and the target plate. This wave initiates from the periphery at the impact face and propagates toward centers of the plates. This wave disrupts the well-characterized and nominally one-dimensional nature of the loading waves. In the analysis and discussion, attention is focused on the part of the experiment before this unloading wave arrives at the rear surface of the target plate ($t_7$). The useful window for data analysis for the velocity profiles recorded on the rear surface is therefore $t_7$-$t_1$ which is approximately 6.38 $\mu$s for the experimental configuration used.

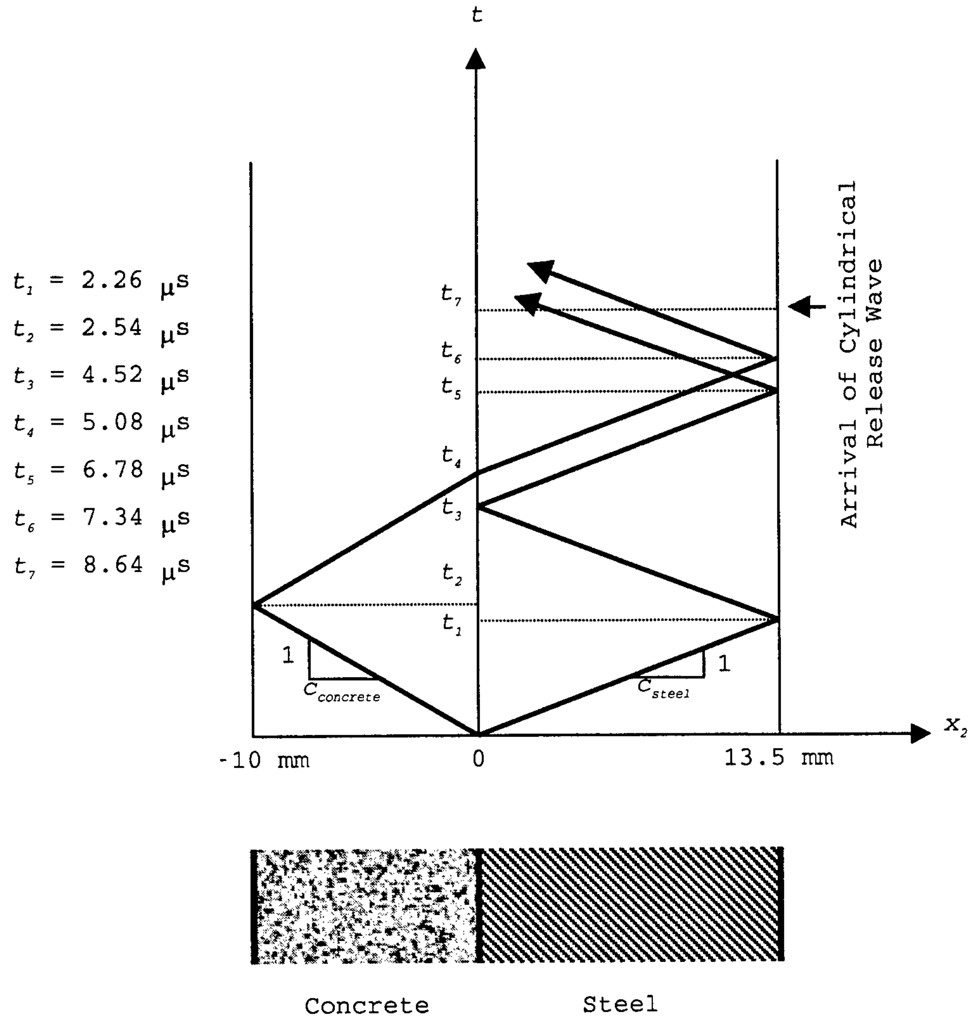


*Fig. 8. Time-distance diagram for the plate impact experiment based on linear elastic material behavior*

The experiment is designed such that the target steel plate remains elastic throughout the impact process. Although the stress and velocity at the impact face are not uniform due to the inhomogeneous specimen properties, elastic wave propagation in the target plate allows the stress and velocity to become more uniform as they approach the rear surface of the target plate. This wave propagation process can be used as a mechanism for obtaining an average measure for the stress history at the impact face. According to the one-dimensional elastic wave theory, this average stress is related to the free surface particle velocity through

$$\sigma(t) = \frac{1}{2}\rho c \mathrm{V}_{\mathrm{fs}}(t), \tag{1}$$

where $\sigma$, $V_{fs}$, $\rho$ and $c$ are, respectively, the average longitudinal stress at the specimen/target interface, particle velocity at the rear surface of the target, mass density and longitudinal wave speed of the anvil material. Equation (1) allows the history of the longitudinal stress carried by the specimen to be inferred from the velocity history measured at the rear surface of the anvil plate.

Impact experiments conducted on mortar and concrete involve projectile velocities between 277 $ms^{-1}$ and 330 $ms^{-1}$. First, the effect of material heterogeneity on the velocity measurement is analyzed. Figure 9 shows the free surface velocity histories measured at four different locations (as indicated in Fig. 1) on the rear surface of the anvil plate during an impact experiment on concrete. The impact velocity is 277 $ms^{-1}$. The corresponding average stresses interpreted from (1) are shown on the secondary vertical axis. The profiles show that the velocity begins to increase when the compressive wave arrives at the rear surface of the anvil plate at approximately 2.2 $\mu$s after impact. The average value of the free surface velocity remains essentially constant until the wave reflected from the specimen/anvil interface arrives at the free surface of the anvil plate. The sudden increase in velocity at $t \cong 6.8$ $\mu$s coincides with $t_5$ in Fig. 8. The four independent measurements show variations from each other. While the oscillations are not coordinated, the average values for the duration of interest between $t_1$ (2.2 $\mu$s) and $t_5$ (6.8 $\mu$s) are quite consistent. Specifically, the average velocity before the arrival of the reloading wave is approximately 58 $ms^{-1}$ and the corresponding average stress is approximately 1.2 GPa. Furthermore, the level of oscillation is the same for all four profiles or approximately 20 $ms^{-1}$ in terms of the velocity. It appears that any of the four curves can appropriately represent the response of the specimen, as long as the focus is on the average stress and the associated oscillation is accepted. The growing deviation of the center profile from the off-center profiles beginning at 8.7 $\mu$s coincides with the arrival of the cylindrical unloading wave at the outer probes ($t_7$ in Fig. 8). The part of the profiles beyond $t_5$ (6.8 $\mu$s) is not used to make interpretations concerning the load-carrying capacities of the specimen materials.

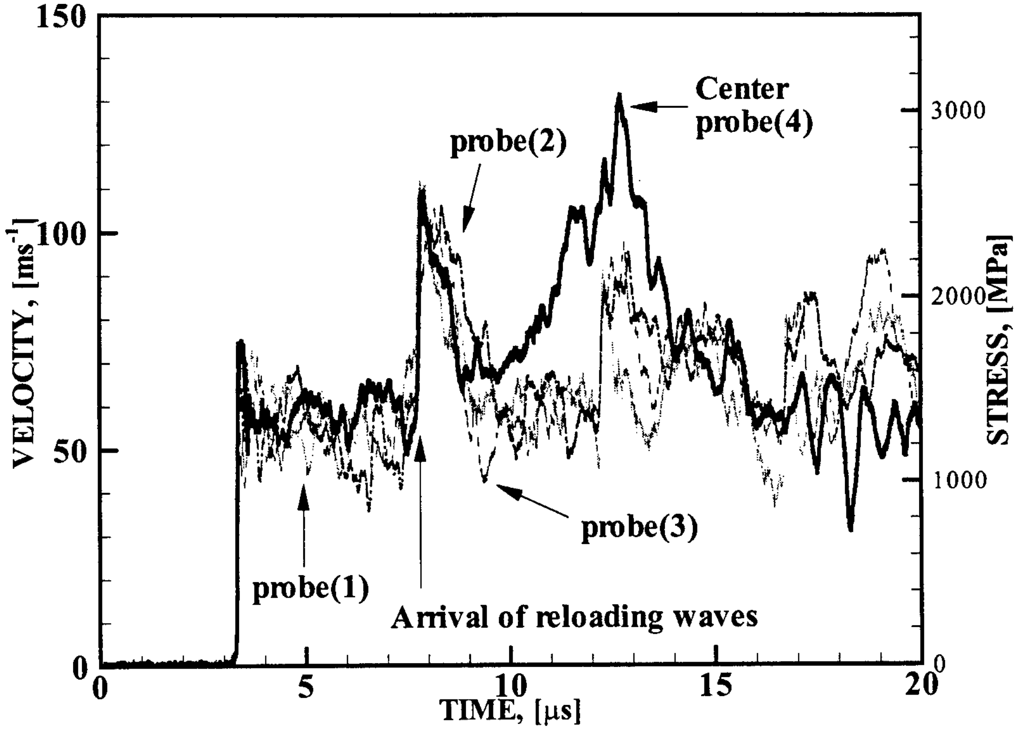


*Fig. 9 Multiple velocity profiles measured at the rear surface of the target plate during an impact experiments on concrete*

This configuration is used to determine the rate-dependence if stress-carrying capacity of concrete and mortar. For mortar, the average stress for $V_0$ = 290 $ms^{-1}$ and 330 $ms^{-1}$ is 1.2 GPa and 1.3 GPa, respectively. In contrast, the average stress carried by concrete is approximately 1.55 GPa for $V_0$ = 290 $ms^{-1}$ and 1.7 GPa for $V_0$ = 330 $ms^{-1}$. Note that the strength of the mortar is approximately 46 MPa under the condition of quasistatic, uniaxial stress. The stress levels here are also at least 8 times those observed in Hopkinson bar experiments. The marked increase in stress-carrying capacity is attributed to the effects of the high strain rates (on the order of $10^4$ $s^{-1}$) and the high lateral confining pressures (over 1 GPa). Based on the rate sensitivity characterization for mortar and using an average strain rate of $10^4$ $s^{-1}$, approximately 42 % of the strength increase (504 MPa) is attributed to strain rate dependence and 58 % (696 MPa) is attributed to pressure sensitivity.

## 5. PERSONNEL AND RESEARCH SUPPORTED:

| | | | |
|---|---|---|---|
| 1. | ***Dr. Min Zhou*** | Assistant Professor | PI/PD |
| 2. | **Dr. *Sunwoo Park*** | Postdoctoral Scientist | Investigator |
| | Research: | Constitutive and Failure Behavior of Granular Materials | |
| 3. | ***Qingxi Xia*** | M.S. & Ph.D. | Graduate Student |
| | Thesis: | Finite Element Modeling of the Dynamic Response of Concrete<br>*(M.S. degree received 3/98)* | |
| 4. | ***Douglas Lucas Grote*** | M.S. | Graduate Student |
| | Thesis: | Experimental Investigation of the Dynamic Deformation and Failure of Concrete and Mortar<br>*(M.S. degree received March 1999)* | |
| 5. | ***Andrew Keller*** | M.S. | Graduate Student |
| | Thesis: | Microstructural effects on Failure Behavior<br>*(in progress)* | |
| 6. | ***Jason Tsai*** | Undergraduate student | January to June 1996 |
| 7. | ***Erik Hall*** | Undergraduate student | August 1996 to September 1997 |
| 8. | ***Akwate Watkins*** | Undergraduate student | Sept. 1996 to Dec. 1997 |
| 9. | ***Kevin Starkes*** | Undergraduate student | September 1997 to present |
| 10. | ***Dawn Amos*** | Undergraduate student | June to August 1997 |

## 6. PUBLICATIONS AND PRESENTATIONS

### A. Thesis

1. Qingxi Xia, Numerical and experimental analysis of the dynamic behavior of concrete and mortar, Georgia Institute of Technology M.S. thesis, March 1998;
2. Douglas Lucas Grote, An experimental study of the constitutive and failure behavior of concrete and mortar under impact loading, Georgia Institute of Technology M.S. thesis, March 1999;

### B. Refereed Publications:

1. D. L. Grote, S. W. Park and M. Zhou, "Dynamic Behavior of Concrete and Mortar at High Strain rates, Part I: Experimental Characterization", submitted to International Journal of Impact Engineering, 1999;
2. S. W. Park, Q. Xia and M. Zhou, "Dynamic Behavior of Concrete and Mortar at High Strain rates, Part II: Numerical Simulations", submitted to International Journal of Impact Engineering, 1999;
3. S. W. Park and M. Zhou, "Separation of Elastic Waves in Split Hopkinson Bars using One-point Strain Measurements", submitted to Experimental Mechanics, 1998;
4. J. Zhai and M. Zhou, "Finite Element Analysis of Micromechanical Failure Modes in Heterogeneous Brittle Solids", accepted for publication in International Journal of Fracture, special issue on *Failure Mode Transition in Solids*, R. C. Batra, Y. D. S. Rajapakse, and A. J. Rosakis, eds., 1998;
5. M. Zhou and R. J. Clifton, "Dynamic Ductile Rupture under the Conditions of Plan Strain", International Journal of Impact Engineering, **19**, pp. 189-206, 1997;

### C. Other Publications:

1. J. Zhai and M. Zhou, Micromechanical Modeling of Fracture in Heterogeneous Solids, *Proceedings of the Sixth Pan American Congress of Applied Mechanics*, pp. 1011-1014, Rio de Janeiro, Brazil, January 4 - 8, 1999;
2. Q. Xia, L. Grote and M. Zhou, "Dynamic Deformation and Failure Behavior of Concrete at High Strain Rates", Proceedings of the 12th ASCE Engineering Mechanics Conference, pp. 1307-1310, 1998;
3. S. W. Park and M. Zhou, "An Improved Analysis Technique for Impact Experiments on Composites using the Split Hopkinson Pressure Bar", Fifth International Conference on Composites Engineering (ICCE/5), pp. 1021-1022, July 5-11, 1998, Las Vegas, NV;

### C. Other Publications (papers to be submitted soon, co-authors are current students and postdoc)

1. D. L. Grote and M. Zhou, "Dynamic failure Behavior of Mortar under Impact Loading", to be submitted to Int. J. Impact Engineering, 1999.

### D. Presentations: (♦ invited talk)

1. Micromechanical Modeling of Fracture in Heterogeneous Solids, *Sixth Pan American Congress of Applied Mechanics*, Rio de Janeiro, Brazil, January 4 - 8, 1999; ♦
2. An Experimental Characterization of the Dynamic Impact Failure of Mortar, American Physical Society (APS) 11th Topical Conference on Shock Compression of Condensed Matter, Snowbird,

Utah, June 27-July 2, 1999, with D. L. Grote;

3. "Dynamic Behavior of Concrete at High Strain Rates", ACI 1998 Fall Convention, Oct. 25-30, 1998, Los Angeles, CA, with S. W. Park and Q. Xia;
4. "Dynamic Deformation and Failure Behavior of Concrete at High Strain Rates", 12th ASCE Engineering Mechanics Conference, San Diego, CA, May 17-20, 1998;
5. "*Ductile Shear Failure during Deformation Localization*", ASME Mechanics & Materials Conference, Symposium on Ductile Damage and Failure Mechanics, McNU'97, June 29-July 2, 1997, Northwestern University, Chicago;
6. "*Time-resolve analysis of the dynamic behavior of granular materials*", AFOSR Particulate Materials and Shock Physics Contractor/Grantee Conference, Lansdown, VA, February 3-5, 1997;
7. "*The growth of shear bands in composite microstructures*", ASME international congress and exposition, Atlanta, GA, Nov., 1996;